



RESEARCH MEMORANDUM

HEAT TRANSFER TO BLUNT NOSE SHAPES WITH LAMINAR
BOUNDARY LAYERS AT HIGH SUPERSONIC SPEEDS

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SUMMARY

A method of designing low heat transfer bodies is devised on the premise that the rate of heat transfer to the nose will be low if the local velocity is low, while the rate of heat transfer to the afterbody will be low if the local density is low. A typical body which results from this design method consists of a flat nose followed by a highly curved, but for the most part slightly inclined, afterbody surface. Several bodies of this type were tested in the Ames 10- by 14-inch supersonic wind tunnel at Mach numbers from 3.0 to 6.3 and it was found that their average heat-transfer rates are substantially less than those for a cone of the same base area and about the same drag. Comparison of experimental results with theory indicates that near the shoulder of a typical flat nose shape local heat-transfer rates are higher than average and that over most of the afterbody local heat-transfer rates are lower than average.

INTRODUCTION

It is a well-known fact that blunting can reduce the rate of heat transfer to the nose of a body in supersonic flow. It is a problem, however, to determine which type of blunting tends to minimize the heat-transfer rate. The purpose of this paper is to describe an investigation of this problem in which it was undertaken first to devise a method of designing blunt shapes and then to check by experiment the effectiveness of these shapes in reducing heat-transfer rate.

THEORY AND DESIGN

The basic heat-transfer equation, in the form of Reynolds analogy, is shown at the top of figure 1. Although this analogy is not strictly

applicable for blunt shapes, in general it can be said that the convective heat-transfer coefficient is proportional to the product of the local density, local velocity, specific heat, and local skin-friction coefficient. The specific heat is a factor over which relatively little control can be exerted. Likewise, control over the skin-friction coefficient is limited primarily by the extent to which the boundary layer can be induced to remain laminar. Attention is therefore focused on the product of the local density and the local velocity. This product, and hence the local heat-transfer coefficient, may be kept low over a shape designed to have low velocities at the nose and low densities over the afterbody. Such a shape would, in its simplest form, be a truncated cone since the flat nose minimizes local velocities, while the highly inclined sides minimize local pressures and hence densities. The fact is, however, that the sharp corner at the intersection of the face and afterbody of a truncated cone tends to cause local separation and reattachment of the flow with an attendant shock wave and unfavorable pressure gradient. These conditions tend to promote transition to a turbulent boundary layer, thereby increasing the local heating rate. Therefore, one is led to believe that the surface in this shoulder region should be curved to avoid local separation and possible tripping of the boundary layer. In order to promote laminar flow over the entire afterbody it is desirable to have a contour which generates a continuously favorable pressure gradient. Such a contour is easily determined with the modified Newtonian theory of Eggers, Resnikoff, and Dennis (ref. 1), provided the square of the hypersonic similarity parameter $M/(L/D)$ is large compared with unity. This condition is satisfied by blunt bodies at the high supersonic Mach numbers of this investigation. The resultant expression defining the shape of the afterbody surface is shown as the second equation in figure 1. Note that the coordinates \bar{x} and \bar{y} are the local x and y dimensions, respectively, divided by the radius of the flat nose. The parameter K in this expression fixes the level and gradient of pressure on the afterbody.

Two families of blunt nose bodies of revolution were designed according to this equation and tested. The first family is shown at the left of figure 1 and consisted of eight bodies having the same fineness ratio, but having various diameters of the flat nose; the two extreme bodies were a 66° cone and a full cylinder corresponding to values of K , of zero and infinity, respectively. For the second family of bodies, shown at the middle right in figure 1, the nose and base diameters were held constant and the fineness ratio was varied from about 0.3 to 1.6. The corresponding values of K are shown on the superimposed sketches of these bodies. The bodies of this second family have approximately the same pressure drag and for this reason two reference bodies of similar pressure drag were included in the test program. These were the sharp pointed and hemispherical-tipped 60° cones shown at the lower right of figure 1. A full hemisphere of the same base diameter was also tested.

EXPERIMENTAL APPARATUS

Tests were conducted in the Ames 10- by 14-inch supersonic wind tunnel at Mach numbers from 3.0 to 6.3. A steady-state heat-transfer technique was used. Heat was transferred into the model from a resistance heater (identified as "main heater" in fig. 2) of Inconel wire wound on a copper spool. From the known resistance and measured voltage the over-all heat-transfer rate could be determined for equilibrium conditions. This apparatus did not permit the measurement of local heat-transfer rates. Models were made of aluminum and provided essentially constant-temperature heat-transfer surfaces because of their high conductivity. Thermocouples were installed within the models to measure temperatures near the outer surface. As shown in figure 2, models were sting supported from the rear and were in effect insulated to prevent heat loss to the support system by a "guard heater" which was used to equalize the temperature in the 0.050-inch support shell. No correction was made to the measured data to take account of the heat flow through the exposed portion of the model bases. This heat flow was estimated to be a small fraction of the total and hence of no concern since the primary interest of this investigation is in the relative effects of shape on heat transfer.

RESULTS AND DISCUSSION

Effect of Bluntness on Heat Transfer

The effect on heat-transfer rate of varying nose diameter while holding fineness ratio constant is shown in figure 3. Representative data at zero angle of attack and free-stream Mach number, M , of 4.24 are presented in the form of dimensionless heat-transfer coefficients, that is, Stanton numbers, based on free-stream properties. At the top of the figure, Stanton numbers are referenced to model base area and as such are a direct comparison of the total heat-transfer rates. As nose diameter is increased from zero, Stanton number first decreases, then remains nearly constant up to a diameter ratio of $1/2$, and thereafter increases substantially up to a diameter ratio of 1. The Stanton numbers presented in the lower part of figure 3 are referenced to wetted area, exclusive of the base, and hence are indicative of the average heating rate per unit surface area. Note that they decrease significantly with increasing diameter ratio up to about $1/2$ and then remain essentially constant. These results suggest that a body with a nose-to-base diameter ratio of about $1/2$ is a good compromise for low values of both total and average heat-transfer rate. Furthermore, this amount of bluntness yields drags which are in the range of practical interest for ballistic missile shapes. It was for this reason that a diameter ratio of about $1/2$ (0.52 to be exact) was used in designing the second family of bodies.

Effect of Fineness Ratio on Heat Transfer to Blunt Bodies

Total heat-transfer rate to the bodies of different fineness ratio at zero angle of attack is shown in figure 4 as a function of free-stream Mach number. Comparative data for a hemisphere are also presented. Stanton numbers are referenced to model base area. The upsweep of the data with increasing Mach number results from the decrease of stream Reynolds number R typical of a wind tunnel operating with a fixed supply pressure. As determined from shadowgraph pictures the boundary layer was laminar over the front and sides of all flat-nose bodies at all test conditions. This is in contrast to the reference cones on which boundary-layer transition occurred at Mach numbers 3.0 and 3.5 and is an illustration of the effect of blunting to increase the length of laminar run. In fact, at $M = 3.0$, the length of laminar run was increased by as much as a factor of 4; that is, the laminar run for the $K = 9$ body (nose to base) was four times longer than the distance to transition on the sharp cone as measured on shadowgraph pictures. With laminar boundary-layer flow there is little difference in the total Stanton numbers of all the bodies tested, although values for the flat-nose shapes are less than those for the sharp cone at all Mach numbers. Thus by blunting it is possible to increase surface area and volume by a factor of 3 with no total heat-transfer rate penalty.

When the heat-transfer data of figure 4 are presented as Stanton numbers referenced to wetted surface area, a pronounced effect of fineness ratio is apparent as shown in figure 5. Note, for example, that values of average Stanton number for the $K = 6$ shape are 35 percent lower than those for the sharp cone with all-laminar boundary layer ($M > 4$). The maximum reduction in average Stanton number, for all-laminar flow on both cone and flat-nose body, is 70 percent and was obtained with the $K = 9$ shape at $M = 4.24$. These data are, of course, as with all the data discussed previously in this report, for zero angle of attack. It should be pointed out, however, that no measurable change in Stanton numbers has been observed for the flat-nose shapes at angles of attack up to 3° .

Now, the fact should not be overlooked that in flight at high supersonic speeds the rate of aerodynamic heating is actually proportional to the product of Stanton number and temperature recovery factor when surface temperatures are not too far from ambient temperature. Thus, it is a tacit assumption of the discussion in previous sections that recovery factor is essentially independent of shape. The validity of this assumption is illustrated in figure 6 where average temperature recovery factors based on free-stream conditions are shown as a function of free-stream Mach number. It is apparent that shape has little effect on recovery factor; hence, this factor plays no significant role in our discussion of the effect of shape on heating.

Distribution of Local Heat-Transfer Coefficients

The measurements of over-all heat-transfer rates described in this paper can, at best, give only a qualitative idea of local heating rates. It was therefore undertaken to determine a theoretical distribution of heat-transfer coefficients around one typical shape. The method of Stine and Wanlass (ref. 2) was used to calculate these heat-transfer coefficients. This calculation requires a knowledge of the local flow properties just outside the boundary layer. These properties were derived from experimental pressure distributions such as those shown in figure 7. Also shown in figure 7 are the predicted pressures of the modified Newtonian theory which was used to design the blunt-nose bodies. These predicted pressures are in reasonably good agreement with experiment, the differences being most pronounced in the region of the shoulder of the body. The calculated variation of local heat-transfer coefficient with distance along the body surface is shown in figure 8 where the results of the Stine-Wanlass method, which includes the effect of pressure gradient, are compared at free-stream Mach numbers 3 and 5 with flat plate values taken from the laminar boundary-layer theory of Van Driest (ref. 3). All heat-transfer coefficients are based on local flow properties just outside the boundary layer. Reference values near the stagnation point were computed by the method of Sibulkin (ref. 4). Predicted heat-transfer coefficients remain essentially constant over the first half of the nose flat but then increase to 2 to 3 times this value near the shoulder. (A portion of the curve in this region has been shown as a dashed line because spacing of the pressure taps did not permit an accurate determination of the maximum.) Subsequently, local coefficients decrease sharply to less than one half the initial value and continue in a gradual decline to the base. The notable feature of this prediction is the pronounced increase of heat-transfer coefficients over the fore part of the body as a result of three-dimensional and pressure-gradient effects. These relatively large local heating rates indicate that the design of these bodies can be improved upon. Specifically, it appears that a slightly convex nose would tend to reduce the heat-transfer peak at the shoulder by reducing the local density, although at the expense of a slight increase in heat transfer to the nose.

Comparison of Theory and Experiment

Integrated values of the theoretical heat-transfer coefficients for portions of the body surface are compared with experimental measurements in figure 9. The flat-nose and nose-shoulder data were obtained with composite models that isolated the heat-transfer surfaces from the remainder of the body. Agreement is reasonably good over the Mach number range. Both computed and measured Stanton numbers show that roughly 50 percent of the total heat transfer was concentrated in the nose-shoulder

region which has less than 20 percent of the surface area. Thus, on an average basis, heat-transfer rates in this region are greater than those for the rest of the body by a factor of the order of 5.

These results apply only when boundary-layer flow is entirely laminar. A qualitative indication of the effect of transition on total heat-transfer rate was obtained, in one case, by artificially tripping the boundary layer in the shoulder region. The resultant Stanton number is shown as the solid point in figure 9. It is indicated that the over-all heating rate is not substantially increased by the presence of a turbulent boundary layer in the afterbody region of relatively low density flow.

SUMMARY OF RESULTS

The results of this investigation can be summarized as follows:

1. A method of designing blunt shapes has been devised which reduces the rate of heat transfer to a body by virtue of low-velocity flow over the nose and low-density flow over the afterbody.
2. An afterbody curvature has been found which augments the favorable effect of a flat nose in promoting long runs of laminar boundary layer.
3. Total heat-transfer rate to these shapes is the same order as that to cones of about the same drag, while heat-transfer rates per unit of surface area are considerably lower.
4. Comparison of theory and experiment indicates higher than average heat-transfer rates near the shoulder of a typical flat-nose shape and relatively low values over most of the afterbody.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., March 6, 1957

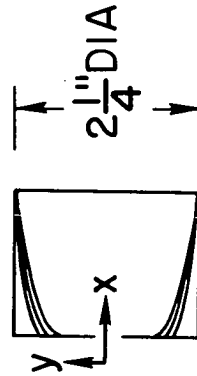
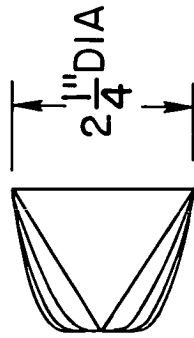
REFERENCES

1. Eggers, A. J., Jr., Resnikoff, Meyer M., and Dennis, David H.: Bodies of Revolution Having Minimum Drag at High Supersonic Airspeeds. NACA TN 3666, 1956. (Supersedes NACA RM's A51K27 by Eggers, Dennis, and Resnikoff and A52D24 by Resnikoff.)

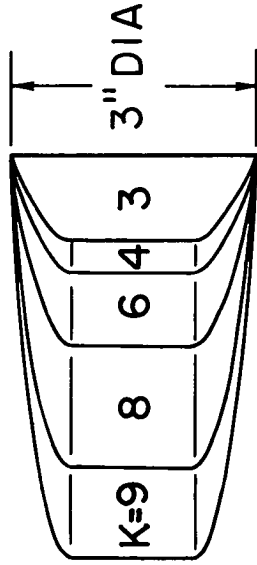
2. Stine, Howard A., and Wanlass, Kent: Theoretical and Experimental Investigation of Aerodynamic-Heating and Isothermal Heat-Transfer Parameters on a Hemispherical Nose with Laminar Boundary Layer at Supersonic Mach Numbers. NACA TN 3344, 1954.
3. Van Driest, E. R.: The Laminar Boundary Layer with Variable Fluid Properties. Rep. No. AL-1866, North American Aviation, Inc., Jan. 19, 1954.
4. Sibulkin, M.: Heat Transfer Near the Forward Stagnation Point of a Body of Revolution. Jour. Aero. Sci. (Readers' Forum), vol. 19, no. 8, Aug. 1952, pp. 570-571.

REYNOLDS ANALOGY $h \propto \rho U C_f$

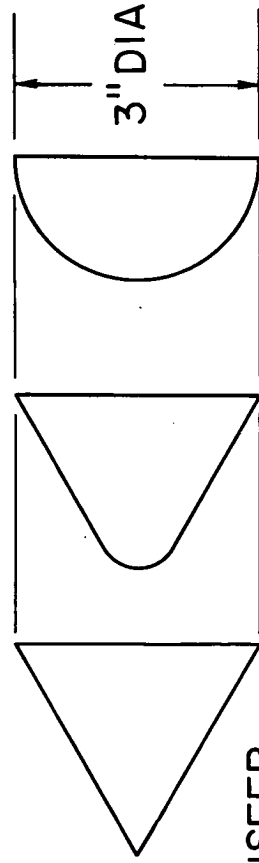
EQUATION OF BODY SHAPE $\bar{X} = \int_1^{\bar{Y}_{MAX}} \sqrt{\bar{Y}^K - 1} \, d\bar{Y}$ WHERE $\bar{X} = \frac{X}{Y_{NOSE}}$, $\bar{Y} = \frac{Y}{Y_{NOSE}}$



BODIES FOR LOW HEAT TRANSFER
FAMILY #1



BODIES FOR LOW HEAT TRANSFER
FAMILY #2



REFERENCE BODIES

Figure 1.- Body shapes used in heat-transfer investigation.

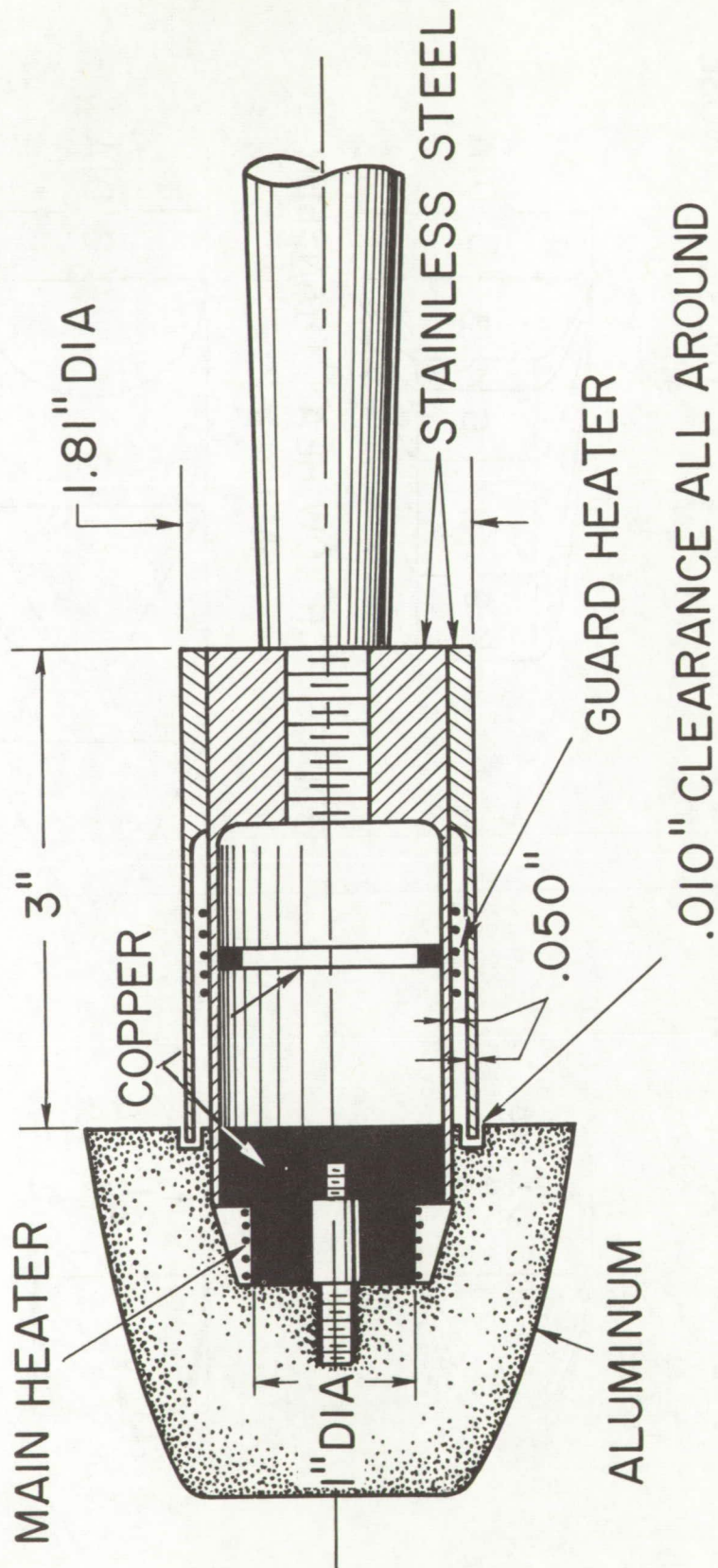


Figure 2.- Heat-transfer apparatus.

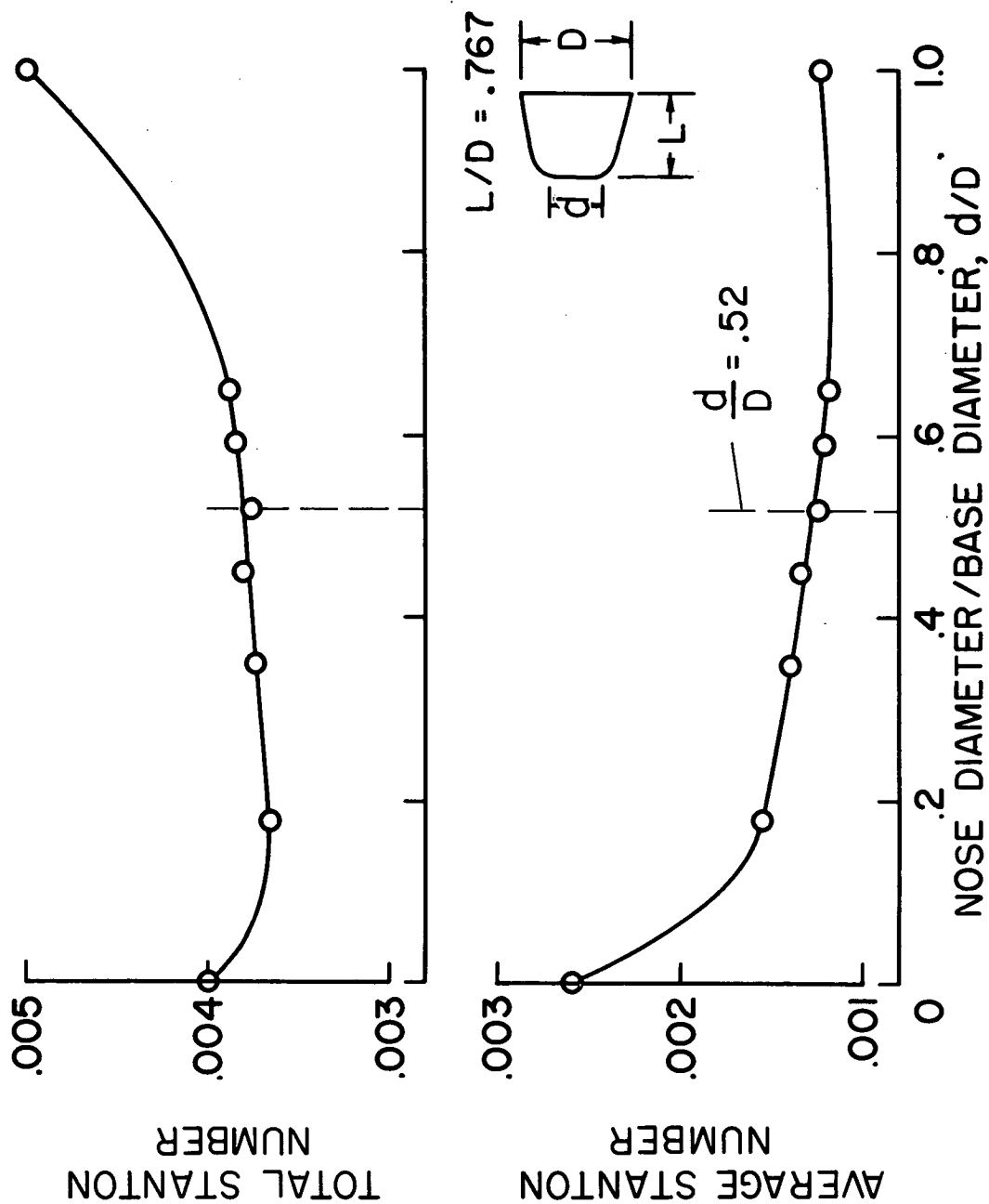


Figure 3.- Effect of bluntness on heat transfer at $M = 4.24$.

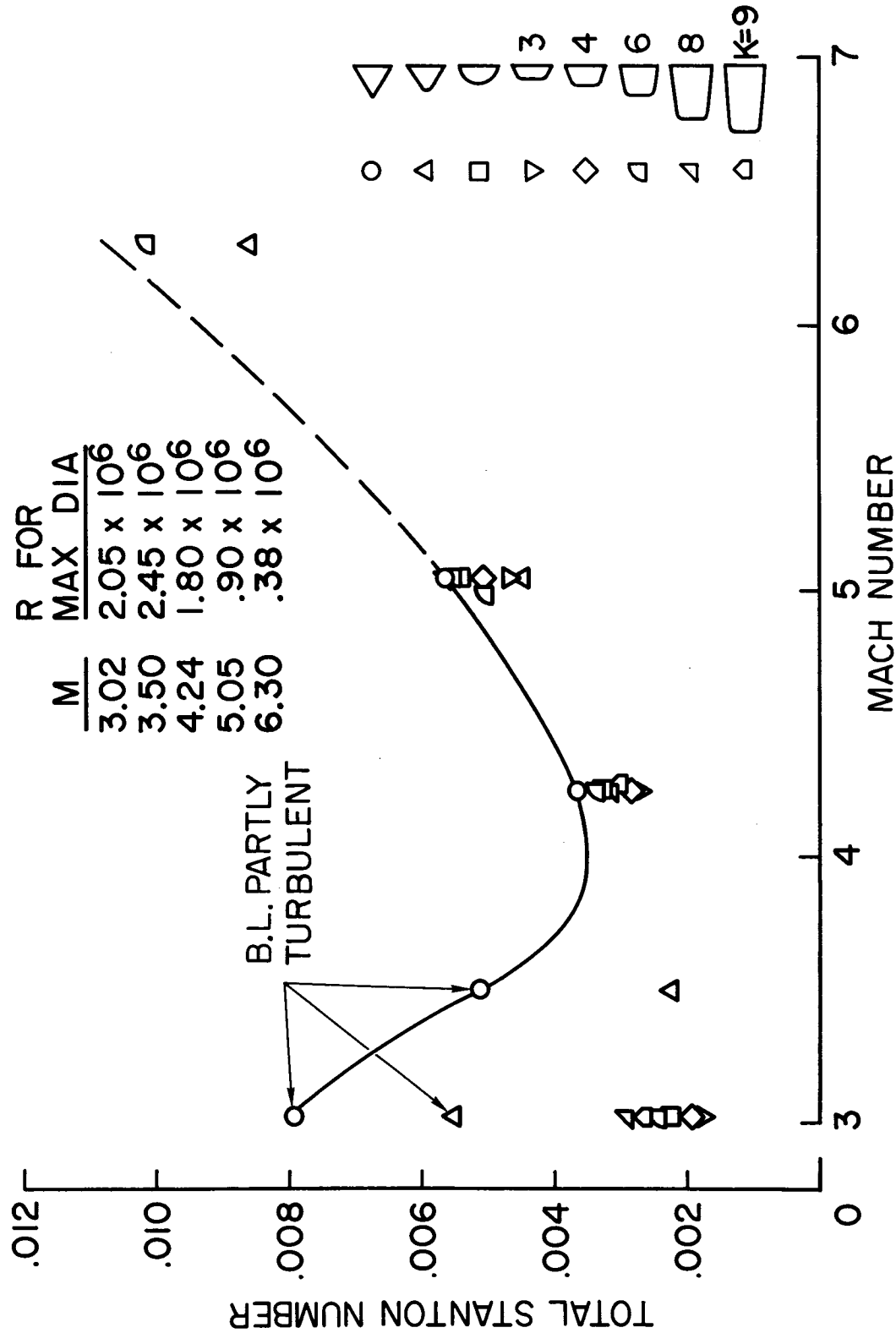


Figure 4.- Total heat transfer to bodies.

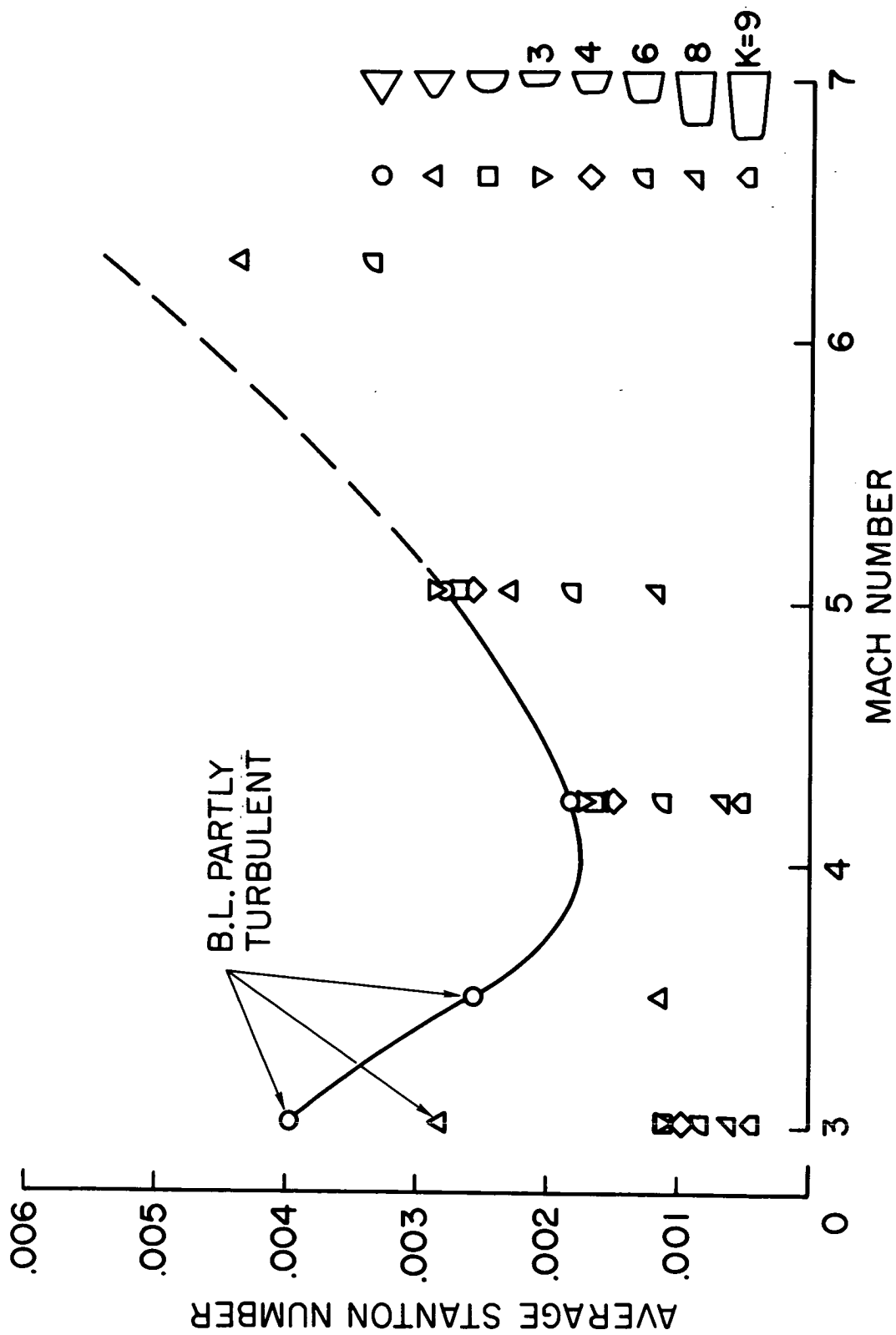


Figure 5.- Average heat transfer to bodies.

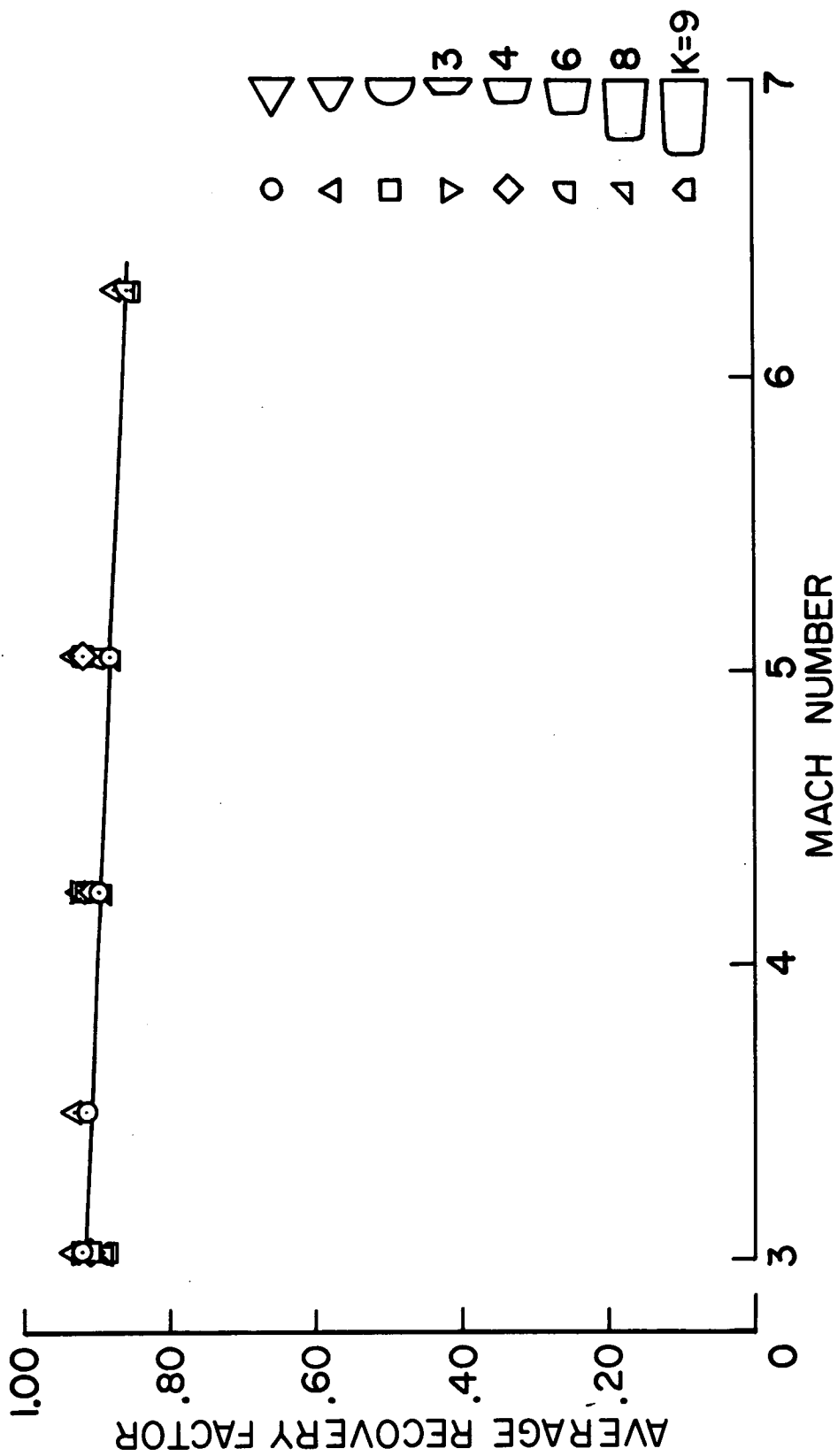


Figure 6.- Average temperature-recovery factors of bodies.

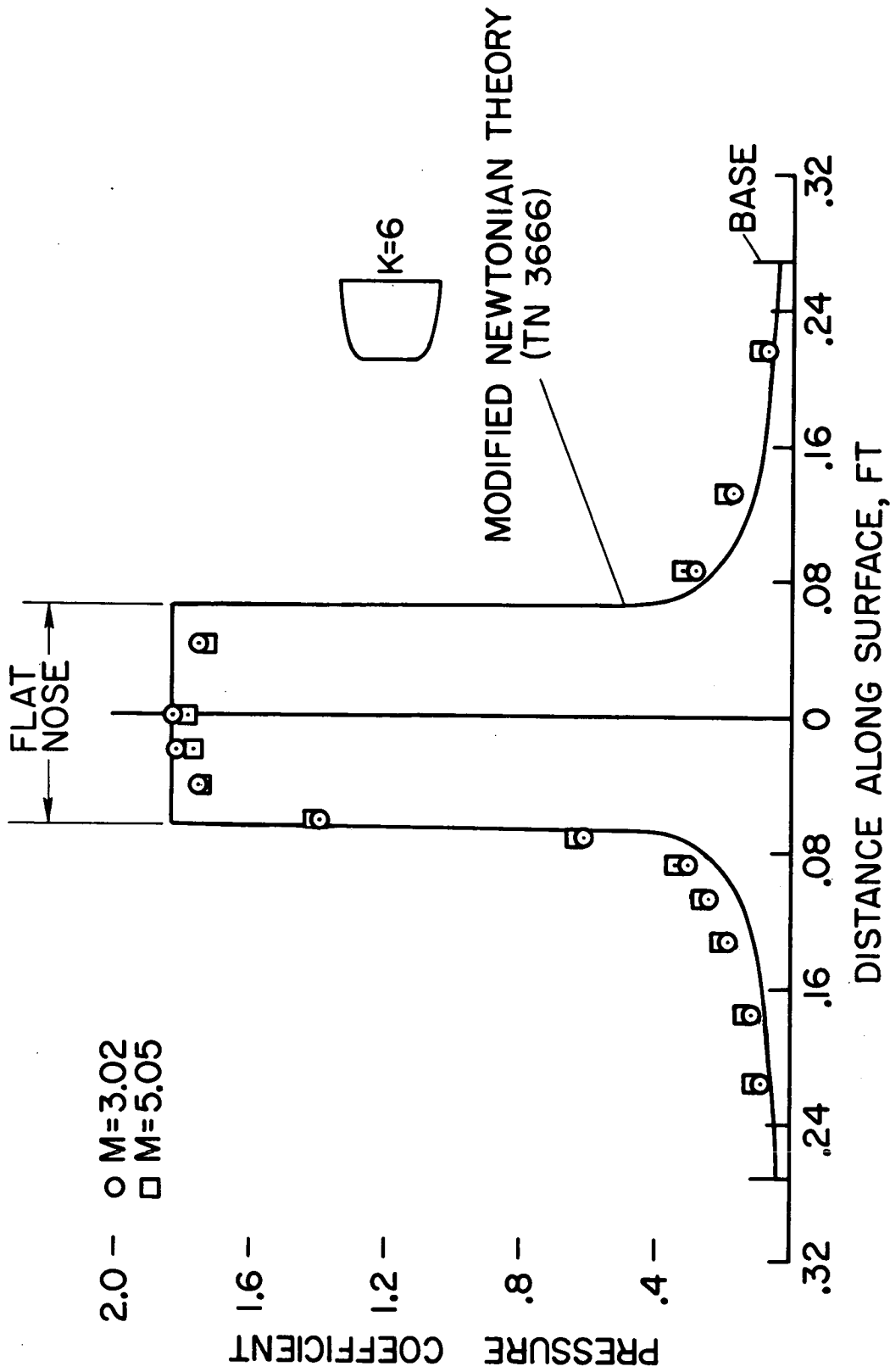


Figure 7.- Pressure distribution about a blunt body.

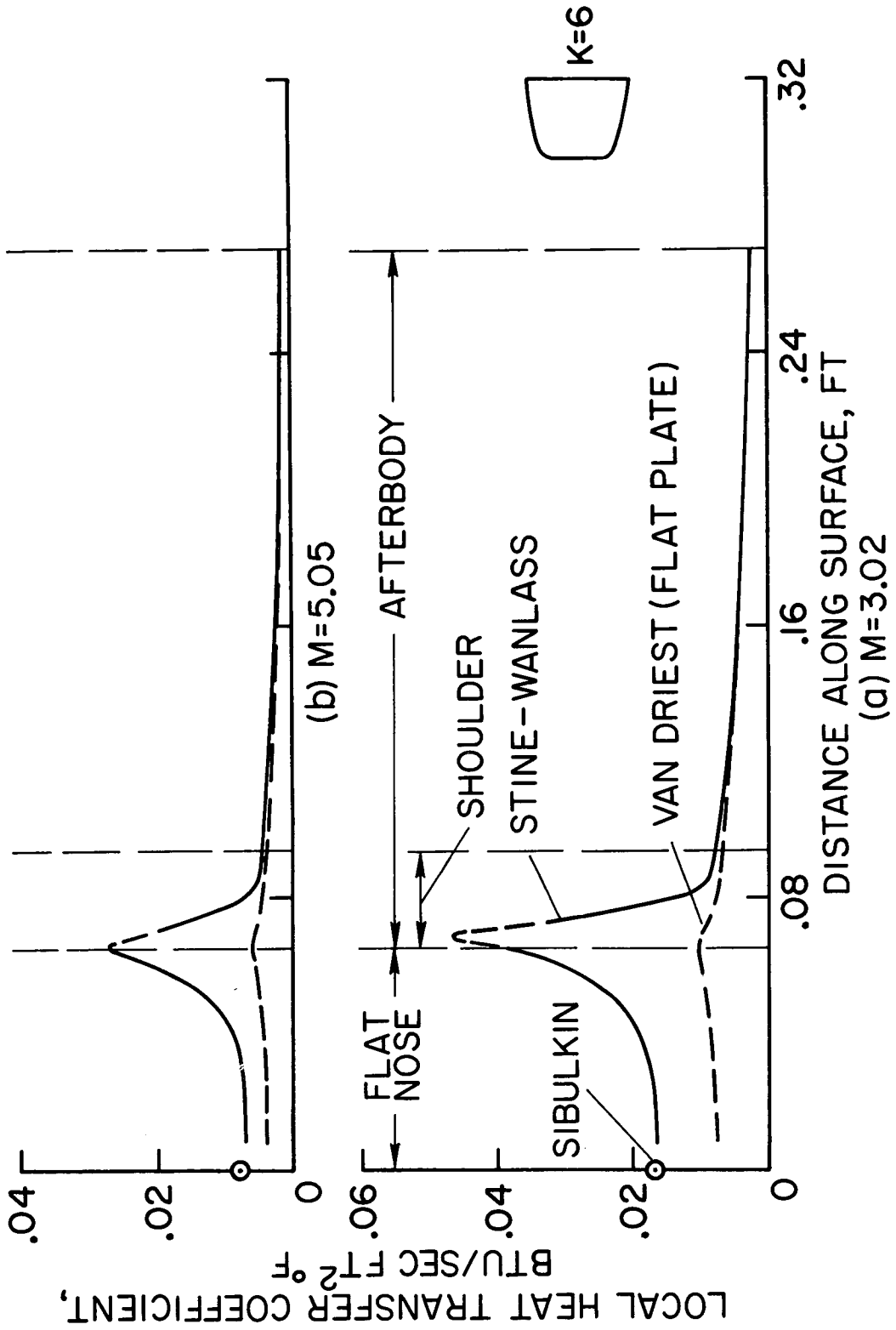


Figure 8.- Theoretical local heat-transfer coefficients for a blunt body; laminar boundary layer.

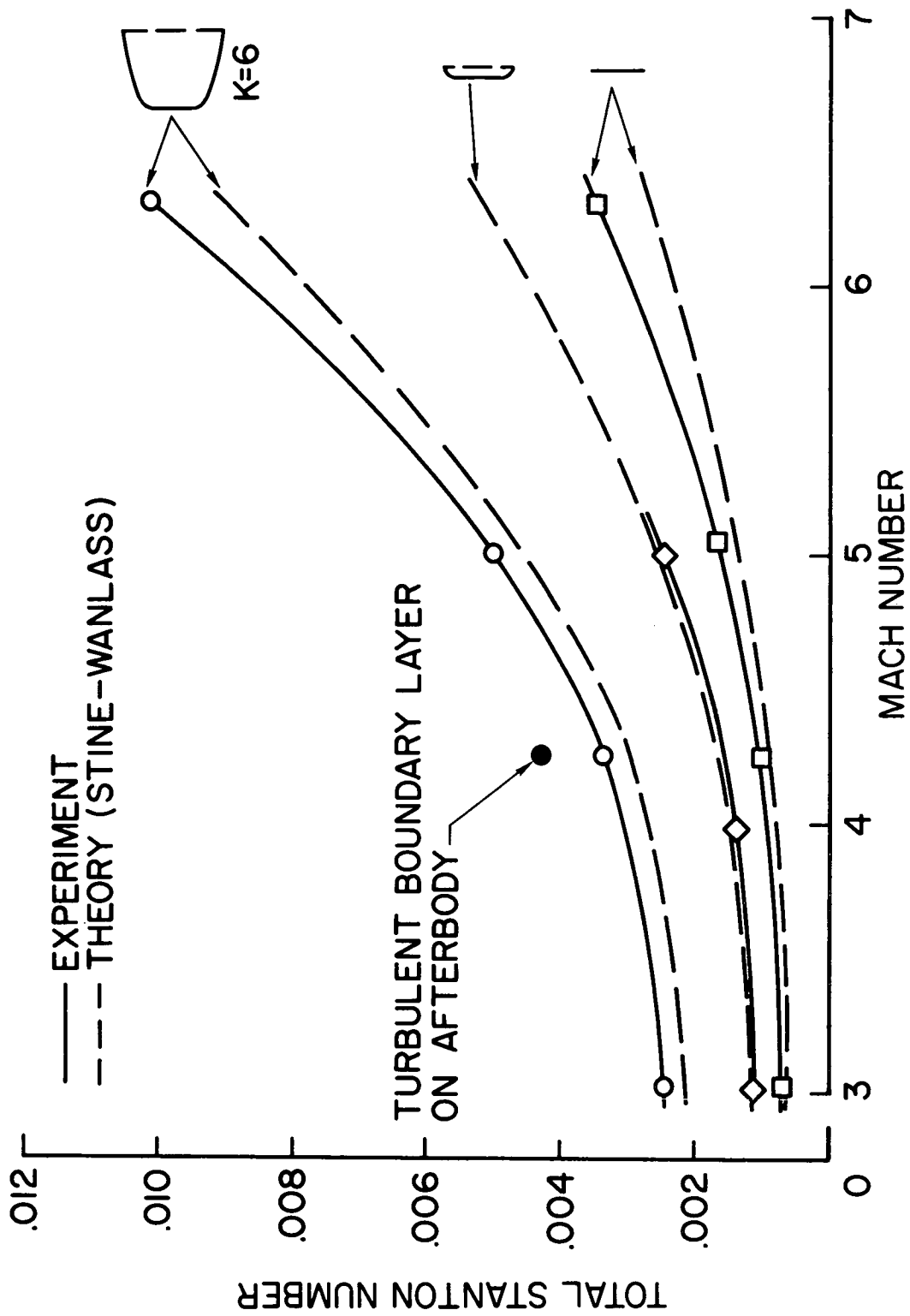


Figure 9.- Heat transfer to a blunt body.